

Spectral Features and Masses in the PeV Region

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An analysis is made of the masses and spectral features for cosmic rays in the PeV region, insofar as they have a bearing on the problem of the interaction of cosmic ray particles.

In our Single Source Model we identified two 'peaks' seen in a summary of the world's data on primary spectra, and claimed that they are probably due to oxygen and iron nuclei from a local, recent supernova. In the present work we examine other possible mass assignments. We conclude that of the other possibilities only Helium and Oxygen (instead of O and Fe) has much chance of success; the original suggestion is still preferred, however. Concerning our location with respect to the SNR shell, the analysis suggests that we are close to it - probably just inside.

1. Introduction

In our Single Source Model (updated version is in [1]) we explained the knee as the effect of a local, recent supernova, the remnant from which accelerated mainly oxygen and iron. These nuclei form the intensity 'peaks' which perturb the total 'background' intensity. The comprehensive analysis of the world's data gives as our datum the plots given in the Figure 1; these are 'deviations from the running mean' for both the energy spectrum mostly from Cherenkov data and the summarised electron size spectrum. It is against these datum plots that our comparison will be made.

In the present work we endeavour to push the subject forward by examining a number of aspects. They are examined, as follows:

- (i) Can we decide whether the solar system is inside the supernova shock or outside it ?
- (ii) Is the identification of Oxygen and Iron in the peaks correct ?
- (iii) Can both the peaks be due to protons rather than nuclei ? In view of claims from a few experiments (DICE, BLANCA) that the mean mass is low in the PeV region, it is wise to examine this possibility.

2. The Solar System's position with respect to the nearby SNR

The appreciation that the frequency of SN in the local region of the Interstellar Medium (ISM) has been higher than the Galactic average, over the past million years, has improved the prospects for the SSM being valid [2,3] and thereby increases the probability that we are close to the surface of a remnant.

It is doubtlessly possible for particles to escape from an SNR shock and propagate ahead. Such a situation has been considered in the 'Berezhko-model'. The problem concerns uncertainties in the diffusion coefficient for the ISM; however, estimates have been made [4,5] and Figure 1 shows the result for the Sun being outside the shock at the distance of $1.5R_S$ for the center of SNR (R_S is the radius of the remnant).

It is seen that the result does not fit well the datum points at all. The model tested must be rejected in its given form.

It is possible to restore it by taking an energy spectrum of more nearly the form for the 'inside SNR' location or at the position outside, but very close to the shell. The corresponding curves are shown in Figure 1 by full lines.

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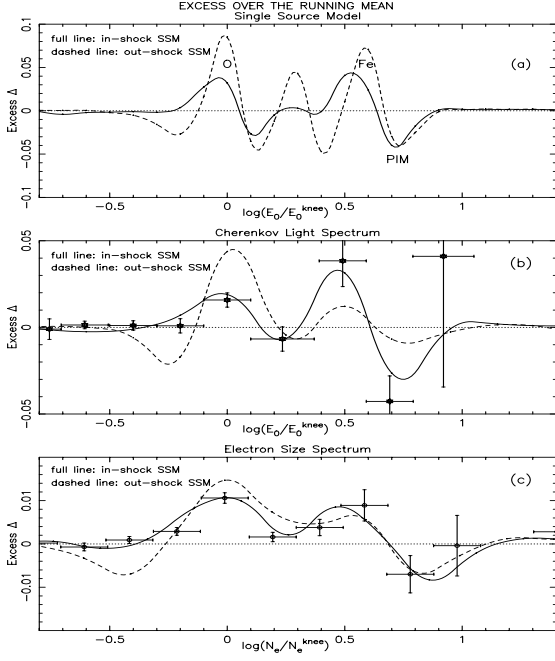


Figure 1. Excess over the running mean for (a) the primary SSM energy spectrum, (b) averaged Cherenkov light spectrum; (c) averaged EAS electron size spectrum. The results relate to the average excess in $\Delta \log(E/E^{knee}) = 0.2$ bins for (b) and (c), for (a) the bin size is 0.1. The full curve is for the case where the Sun is inside the shock as in the original SSM. The dashed line is for the Sun outside of the shock. Curves for SSM and Cherenkov light are without noise corrections, whereas for the electron size spectrum a noise correction, using $\sigma(\log N_e) = 0.16$ has been made.

3. SNR: Helium and Oxygen

A tolerable astrophysical case could be made for helium and oxygen rather than oxygen and iron, and the direct measurements at lower energies than the knee region do not really rule it out.

Figure 2 shows the Δ -values for the corresponding spectra. The separation of the He and O peaks is a little greater than for O and Fe ($8/2$ compared with $26/8$) and this causes the He, O pattern to be displaced somewhat. Although the fit to the datum points is not as good as for O, Fe, the He, O combination cannot be ruled out

on the basis of the Δ -plots alone. The absence of the preferred-by-us nuclei between the two peaks is a worry, though (incertion of carbon does not help to fill the gap between two peaks). The Fe peak would then be expected at $\log(N_e/N_e^{knee}) = 1.1$.

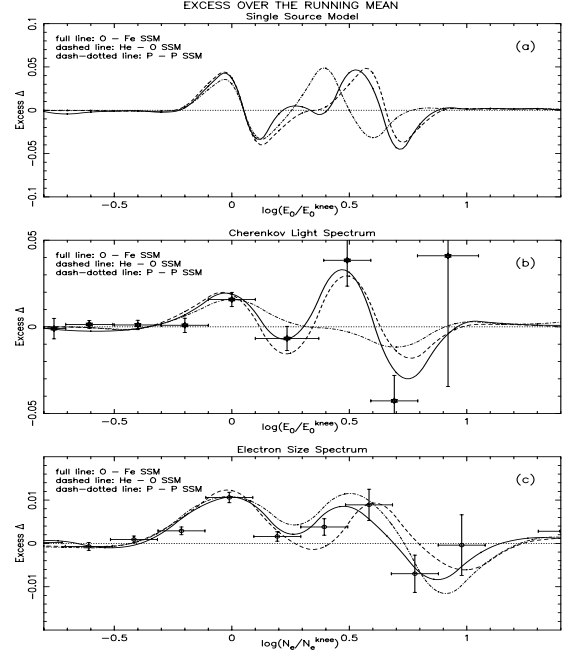


Figure 2. Excess over the running mean for the usual assumption: O, Fe (full line), for He, O (dashed line) and for P-P (dash-dotted line). Although O, Fe gives the best fit, He, O cannot be ruled out, P - P is disallowed.

4. Proton Peaks

Calculations have been made for the case of two proton peaks, the proton spectra having been taken to be the standard interior-to-the SNR form. The result is also shown in Figure 2.

An interesting situation develops here. Although it is possible to tune either the energy spectrum or the size spectrum to fit the Δ -results, it is not possible to choose an energy spectrum

which fits both. This arises because of the sensitivity of the number of electrons at the detection level to the primary mass. In Figure 2 the separation of the proton peaks in the energy spectrum was chosen such that the Δ -distribution for shower size was a reasonable fit to the data. However, the separation of the peaks in the energy spectrum necessary for the shower size fit is less than that for O, Fe by 0.15; the result is that after the necessary binning (0.2 in $\log E$ units) for the energy spectrum there is no agreement there.

5. Discussion about the Nature of the Peaks and our Location

It is evident from the foregoing that the two-proton peak model is unacceptable. This result cast doubt on the analyses of EAS data which conclude that the mean primary mass is 'low' ($\langle \ln A \rangle \simeq 1.5$) in the PeV region. As mentioned already, it is our view that some, at least, of the models used in the mass analyses are inappropriate for the interactions of nuclei, particularly for the production and longitudinal development of the electromagnetic component. It is interesting to know, in connection with mean mass estimates, that the recent work using the Tibet EAS array [6] has given strong support for the result - favoured by us - in which the average cosmic ray mass increases with energy. In fact, their mass is even higher than ours: $\langle \ln A \rangle \simeq 3.1$, compared with our 2.4, at 1 PeV, and 3.3, compared with 3.0 at 10 PeV. Equally significant is the fact that the sharpness of the iron component that they need to fit the overall data is quite considerable: $S = 1.4$. It will be remembered that straightforward Galactic diffusion - the 'conventional model' - gives $S \simeq 0.6$ for any one mass component and $S \simeq 0.3$ for the whole spectrum [7].

Returning to the question of 'our' location with respect to the SNR it seems difficult to account for the Δ -distribution if we are some distance outside the shell, unless the diffusion coefficient for cosmic ray propagation in the ISM is almost energy-independent. We appear to be inside, or only just outside.

Finally, concerning the nature of the peaks: O, Fe or He, O, it is difficult to rule out the latter

from the Δ -plots alone, although the lack of an iron peak is surprising. However, there is some evidence from the Tunka-25 Cherenkov experiment for a further peak at roughly the correct energy for the third (Fe) peak [8]. There is also a hint of a peak in KASCADE spectrum, which is observed at an even higher energy than in Tunka-25 [9]. Most other experiments - but not all - do not have the sensitivity to detect a further peak so the situation here is still open.

We still prefer our original suggestion, viz. that the peaks are due to O and Fe, and their shape is the consequence of the sharp cut-off in the energy spectrum of particles accelerated by SNR. The main reason for the preference is the fact that O and Fe spectra extrapolate and fit direct measurements of those components rather well [10] and there are good astrophysical reasons favouring these nuclei.

6. Conclusions

The Single Source Model, with its explanation of the knee in the cosmic ray energy spectrum in terms of particles (probably principally nuclei of oxygen and iron) from a recent, local SN, has been examined further. It is true that the identity of the nuclei is not completely secure and it is just possible that rather than O, Fe, the combination is He, O: however, we still prefer the original explanation.

The question of the nature of the particles responsible for the knee is, therefore, still somewhat uncertain; however, that there is structure in the spectrum, indicative of a single source, seems to be rather secure.

Turning to our location, the analysis suggests that we are just inside the shell, although, with a different diffusive mode of propagation for the particles we could be just outside it.

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